Linear Collider Detectors

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Fermilab
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- Many open issues for LC detectors
- Physics goals involve low event rates with relatively low backgrounds
  - opportunity for novel approaches

The “next” Linear Collider

The “next” Linear Collider proposals include plans to deliver **a few hundred** fb^{-1} of integrated lum. per year

	TESLA (DESY-Germany)	JLC-C (Japan)	NLC/JLC-X * (SLAC/KEK-Japan)
L_{design} (10^{34})	$3.4 \rightarrow 5.8$	0.43	$2.2 \rightarrow 3.4$
E_{CM} (GeV)	$500 \rightarrow 800$	500	$500 \rightarrow 1000$
Eff. Gradient (MV/m)	$23.4 \rightarrow 35$	34	70
RF freq. (GHz)	1.3	5.7	11.4
Δt_{bunch} (ns)	$337 \rightarrow 176$	2.8	1.4
#bunch/train	$2820 \rightarrow 4886$	72	190
Beamstrahlung (%)	$3.2 \rightarrow 4.4$		$4.6 \rightarrow 8.8$

* US and Japanese X-band R&D cooperation, but machine parameters may differ

Detector Requirements

There is perception that Linear Collider Detectors are trivial

Not true!

But requirements are orthogonal to hadron collider requirements

Here are some comparisons

Tracker thickness:

CMS	0.30 X_0
ATLAS	0.28 X_0
LC	0.05 X_0

Vertex Detector layer thickness

CMS	1.7 % X_0
ATLAS	1.7 % X_0
LC	0.06% X_0

Detector Requirements

Vertex Detector granularity

CMS	39 Mpixels
ATLAS	100 Mpixels
LC (Telsa)	800 Mpixels

ECAL granularity (detector elements)

CMS	76×10^3
ATLAS	120×10^3
LC(Tesla)	32×10^6

Unburdened by high radiation and high event rate, the LC can use

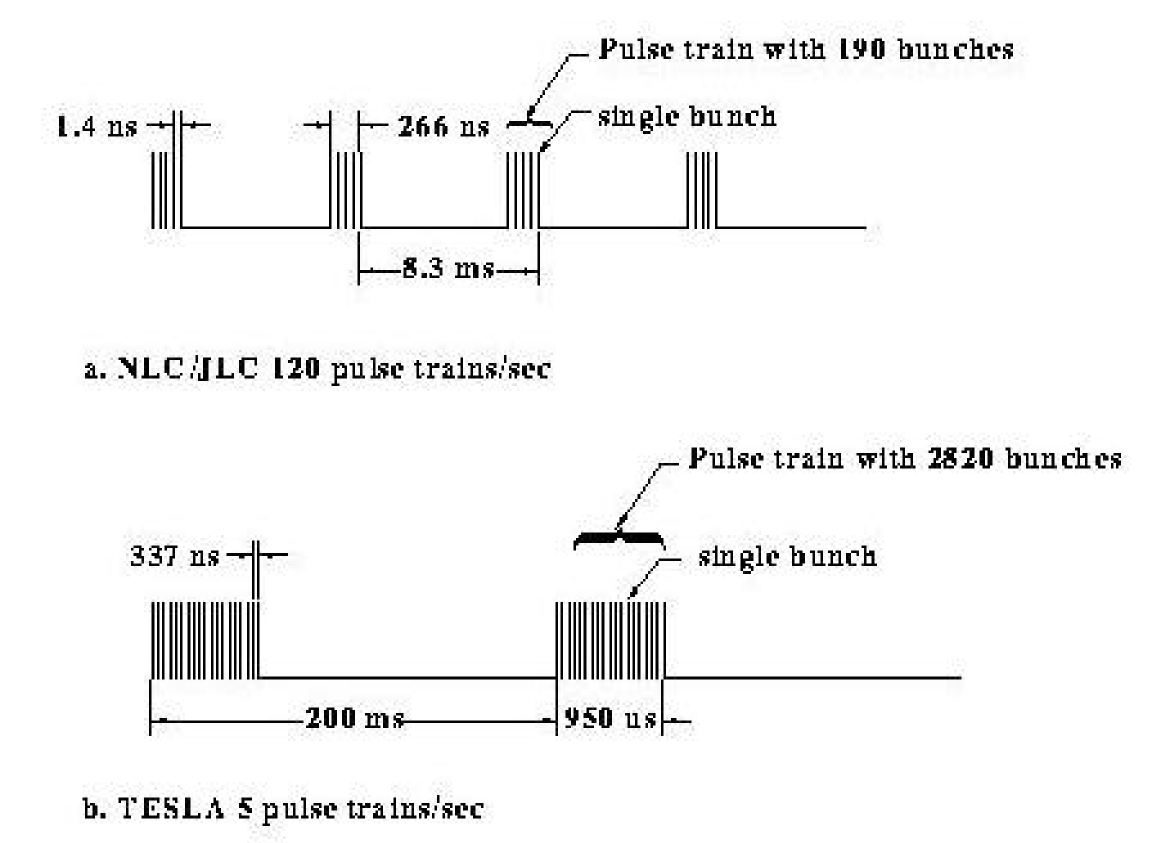
6 times less material in tracker
vxd 3-6 times closer to IP
35 times smaller pixels and 30 times thinner vxd layers
> 200 times higher ECAL granularity (if it's affordable)

IR Issues

Time structure

NLC (JLC)

Tesla



IR Issues

<u>Time structure</u>

NLC (JLC)

190 bunches/train $\Rightarrow$ 1.4 ns bunch spacing

$\Rightarrow$ crossing angle (20 mrad) - (8 mrad for JLC)

might want to time-stamp within train?

Tesla

2820 bunches/train $\Rightarrow$ 950 μsec long

no crossing angle, but could have one

very much higher duty cycle (how to deal with?)

IR Issues

Solenoid effects

transverse component of solenoid must be compensated - straight forward

NLC - L Detector

IR Layout

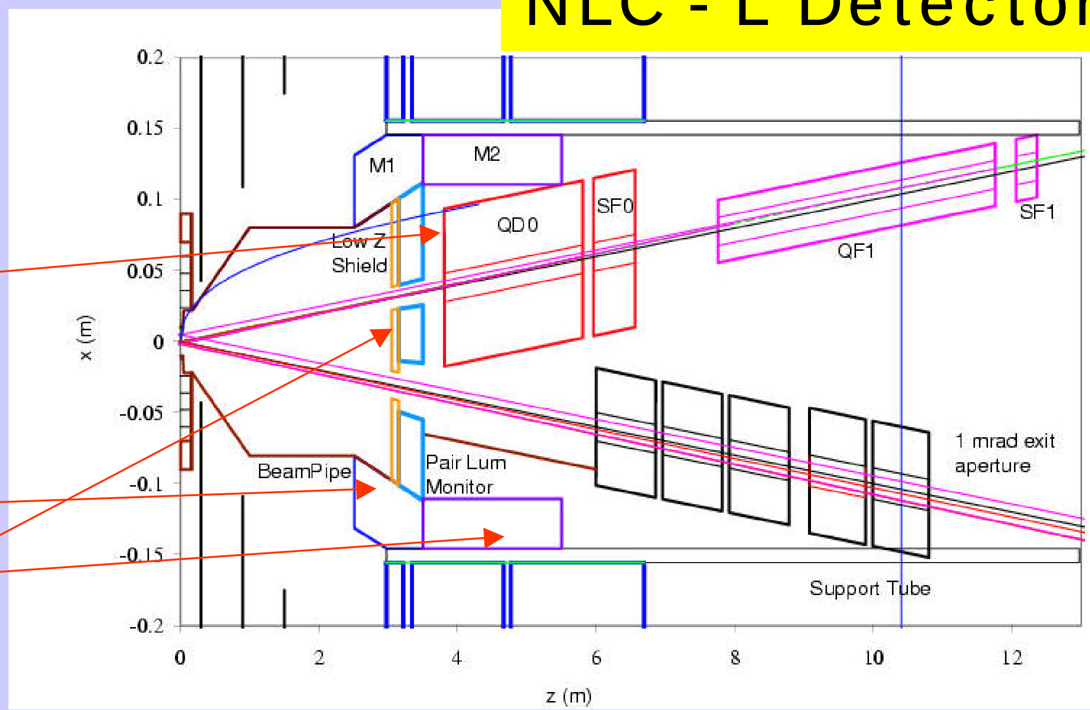
$L^* = 3.8$ m

Masks

M1 - W/Si

M2 - W

Low-Z



IR Issues

Small spot size issues

nm vertical stability required

$\Rightarrow$ permanent magnets for QD0 and QF1

passive compliance + active suppression

15 ns response within bunch train (NLC)

Beam-beam interaction

broadening of energy distribution (beamstrahlung)

~5% of power at 500 GeV

backgrounds

e^+e^- pairs

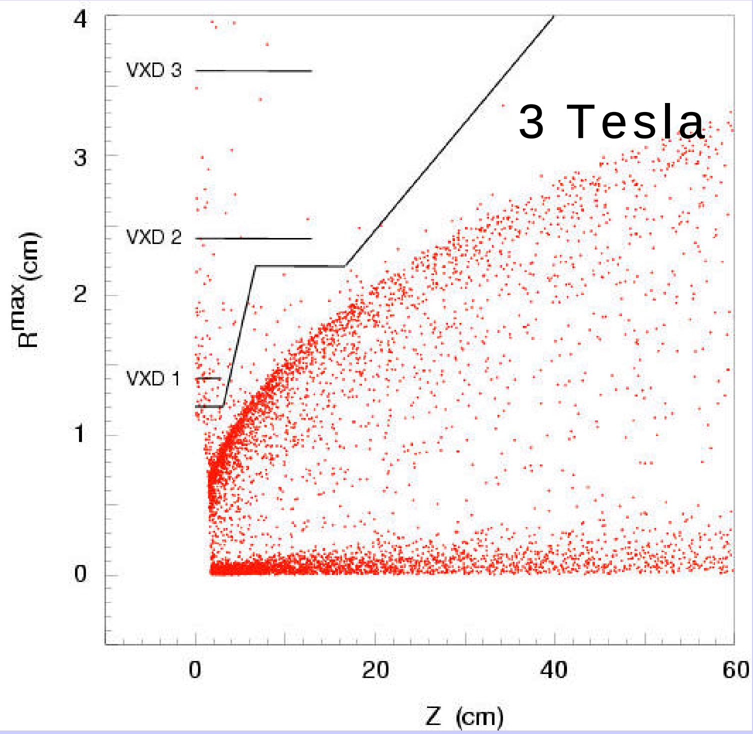
radiative Bhabhas

low energ tail of disrupted beam

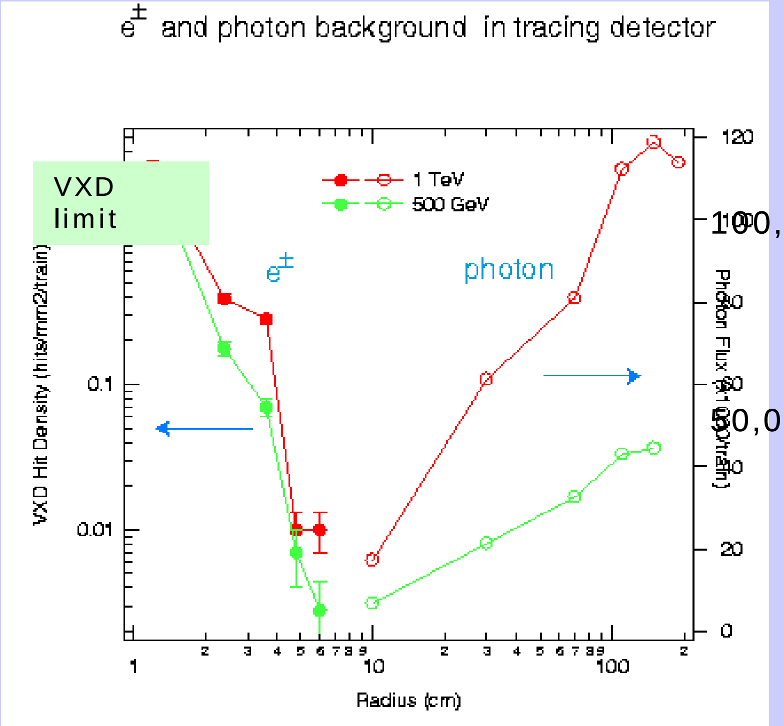
neutron “back-shine” from dump

hadrons from gamma-gamma

IR Issues

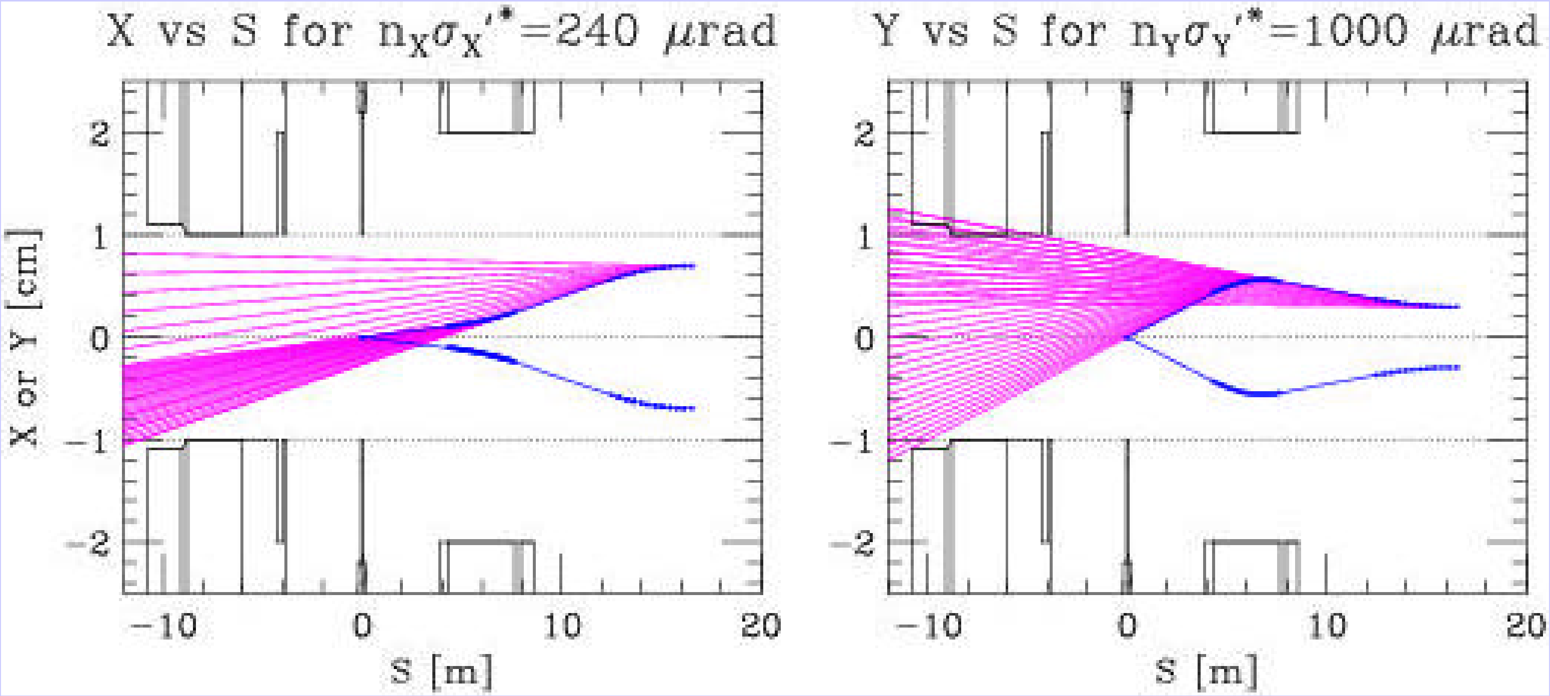


e⁺e⁻ pairs



Hits/bunch train/mm² in VXD, and photons/train in TPC

IR Issues



Synchrotron radiation photons from beam halo in the final doublet

halo limited by collimation system

Detector Requirements

Vertex Detector

physics motivates excellent efficiency and purity

large pair background from beamstrahlung

$\rightarrow$ large solenoidal field ($\geq$ 3 Tesla)

pixelated detector [(20 μm)^2 $\rightarrow$ 2500 pixels/mm^2]

min. inner radius (< 1.5 cm), ~5 barrels, < 4 μm resol,

thickness < 0.2 % X_0

Calorimetry

excellent jet reconstruction

eg. W/Z separation

use energy flow for best resolution

(calorimetry and tracking work together)

fine granularity and minimal Moliere radius

charge/neutral separation $\rightarrow$ large BR^2

Detector Requirements

Tracking

robust in Linear Collider environment

isolated particles (e charge, μ momentum)

charged particle component of jets

jet energy flow measurements

assists vertex detector with heavy quark tagging

forward tracking (susy and lum measurement)

Muon system

high efficiency with small backgrounds

secondary role in calorimetry ("tail catcher")

Particle ID

dedicated system not needed for primary HE physics goals

particle ID built into other subsystems (eg. dE/dx in TPC)

Beamline requirements

Beam energy measurement

- Need 50-100 MeV (10^{-4}) precision
  - SLD WISRD technique is probably adequate (needs work)
  - TESLA plans BPM measurement pre-IP (needs work)
- Luminosity spectrum
  - acolinearity of Bhabhas
  - question - can it be extracted from WISRD?
- What about effect of beam disruption

Polarization measurement

- SLD achieved 0.5% - same technique at NLC should give 0.25%
- TESLA plans only before IP (is this okay? NLC bias says no)
- Positron polarization helps dramatically

LC Detectors

Tesla TDR Detector

American High Energy IR

1.) L

conventional large detector based on the early American L (Sitges/Fermilab LCWS studies)

2.) SD (silicon detector)

motivated by energy flow measurement

JLC Detector

3 Tesla

LC Detectors

TESLA TDR

- “pixel” vertex detector
- silicon/W EM calorimeter (energy-flow)
- 4 T coil

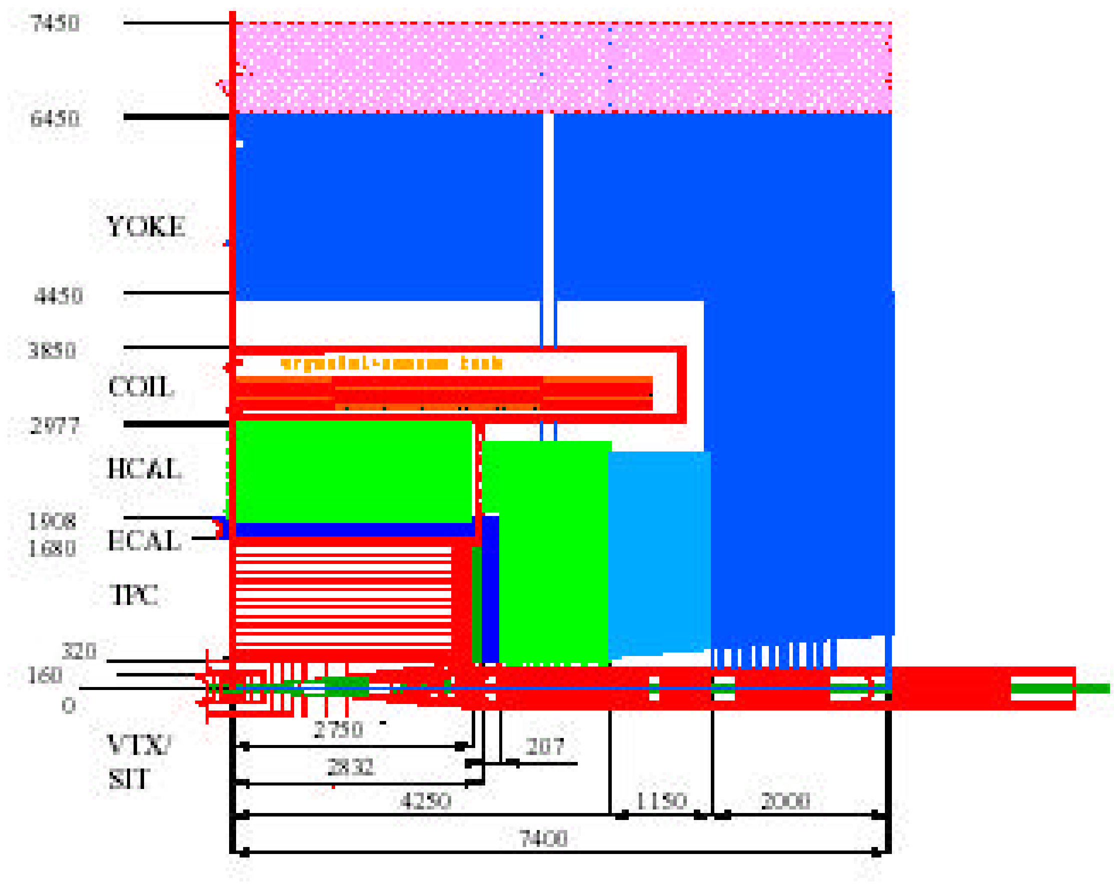
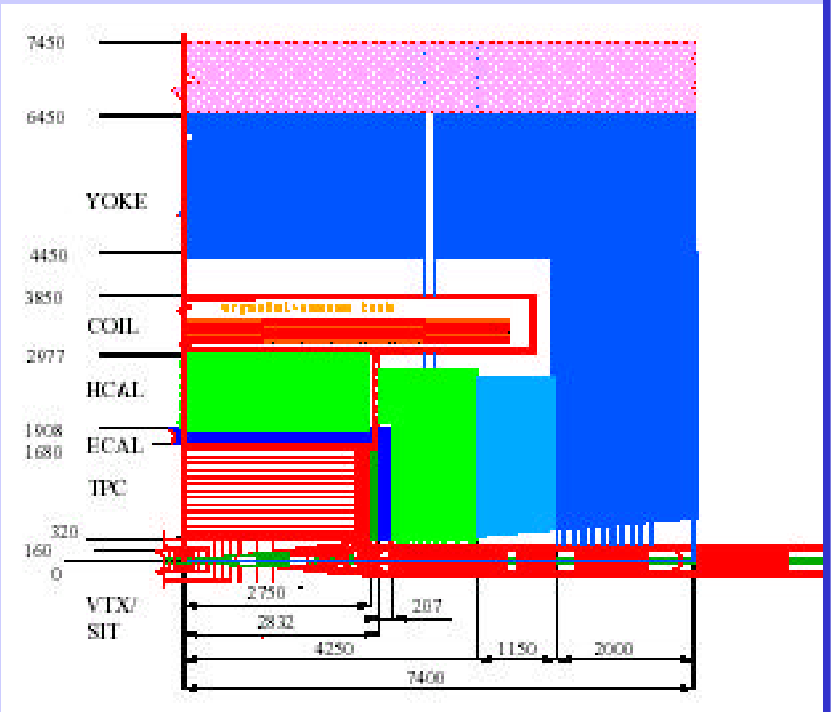


Figure 1.1.1: *View of one quadrant of the TESLA Detector. Dimensions are in mm.*

LC Detectors

- TESLA TDR

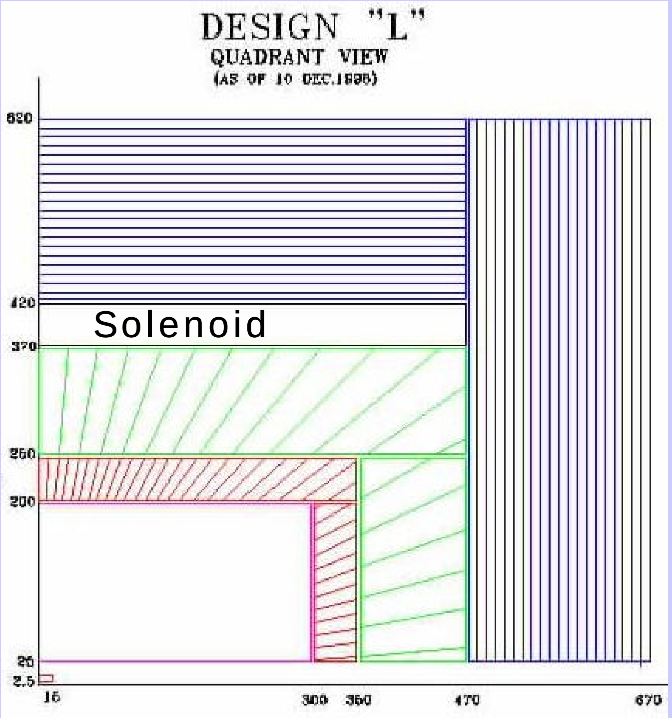


Subdetector	Goal	Technologies
Vertex Detector (VTX)	$\delta(IP_{r\phi,z}) \leq 5\,\mu\mathrm{m} \oplus \frac{10\,\mu\mathrm{m}\,\mathrm{GeV}/c}{p \sin^{3/2}\theta}$	CCD, CMOS, APS
Forward Tracker (FTD)	$\frac{\delta p}{p} < 20\,\%$, $\delta_\theta < 50\,\mu$rad for p=10-400 GeV/c down to $\theta \sim 100$ mrad	Si-pixel/strip discs
Central Tracker (TPC)	$\delta(1/p_t)_{\mathrm{TPC}} < 2 \cdot 10^{-4} (\mathrm{GeV}/c)^{-1}$ $\sigma(dE/dx) \leq 5\%$	GEM, Micromegas or wire readout
Intermediate Tracker (SIT)	$\sigma_{point} = 10\,\mu$m improves $\delta(1/p_t)$ by 30%	Si strips
Forward Chamber(FCH)	$\sigma_{point} = 100\,\mu$m	Straw tubes
Electromag. Calo. (ECAL)	$\frac{\Delta E}{E} \leq 0.10 \frac{1}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$ fine granularity in 3D	Si/W, Shashlik
Hadron Calo. (HCAL)	$\frac{\Delta E}{E} \leq 0.50 \frac{1}{\sqrt{E(\mathrm{GeV})}} \oplus 0.04$ fine granularity in 3D	Tiles, Digital
COIL	4 T, uniformity $\leq 10^{-3}$	NbTi technology
Fe Yoke (MUON)	Tail catcher and high efficiency muon tracker	Resistive plate chambers
Low Angle Tagger (LAT)	83.1–27.5 mrad calorimetric coverage	Si/W
Luminosity Calo. (LCAL)	Fast lumi feedback, veto at 4.6–27.5 mrad	Si/W, diamond/W
Tracking Overall	$\delta(\frac{1}{p_t}) \leq 5 \cdot 10^{-5} (\mathrm{GeV}/c)^{-1}$ systematics $\leq 10\,\mu$m	
Energy Flow	$\frac{\Delta E}{E} \simeq 0.3 \frac{1}{\sqrt{E(\mathrm{GeV})}}$	

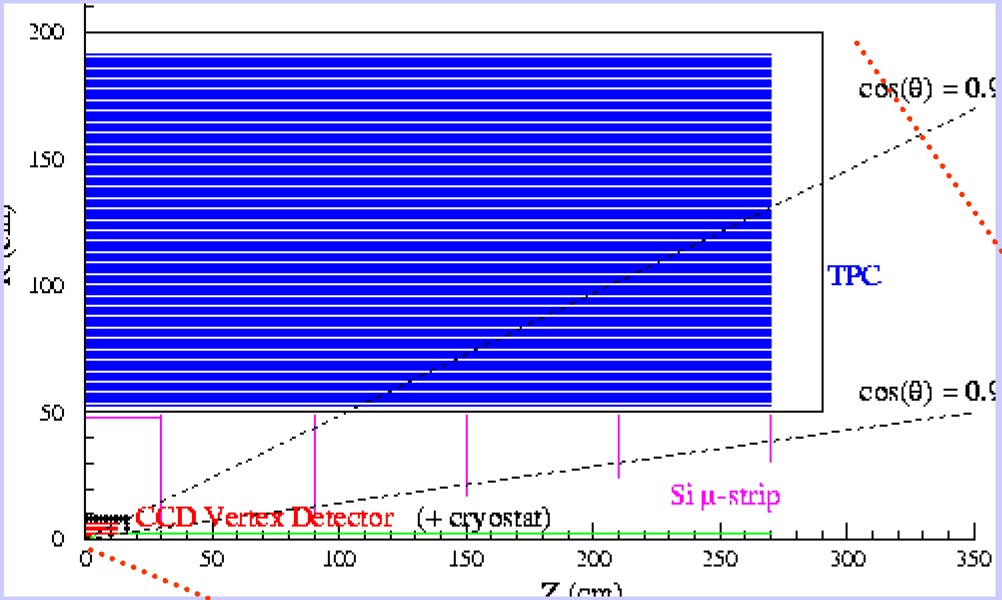
Table 1.3.1: *Detector performance goals for physics analyses for $\sqrt{s}$ up to ~ 1 TeV.*

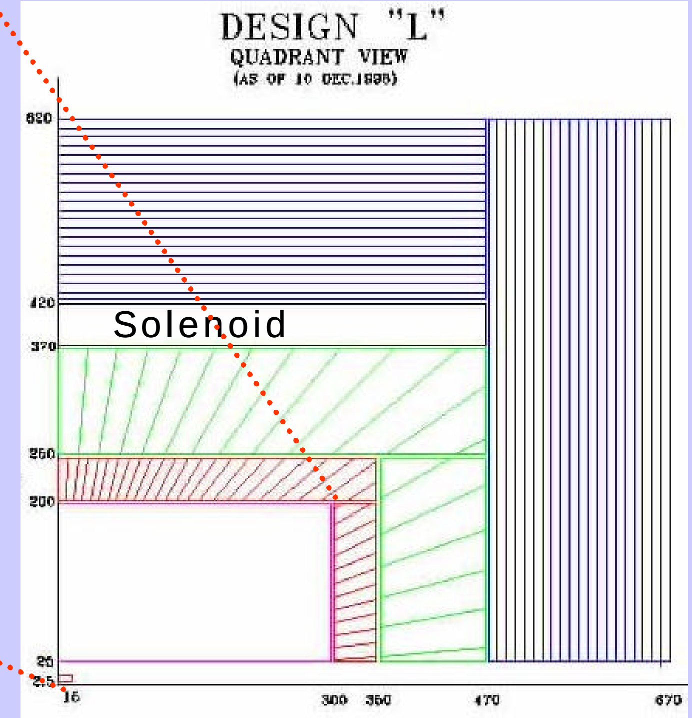
Resource Book L Detector

5 barrel CCD vertex detector
3 Tesla Solenoid
outside hadron calorimeter
TPC Central Tracking (52 $\rightarrow$ 190 cm)
Intermediate Si strips at R=48 cm
Forward Si discs (5 each)
Pb/scintillator EM and Had calorimeter
EM   40 x 40 mrad^2
Had   80 x 80 mrad^2
Muon - 24 5 cm iron plates with gas
chambers (RPC?)



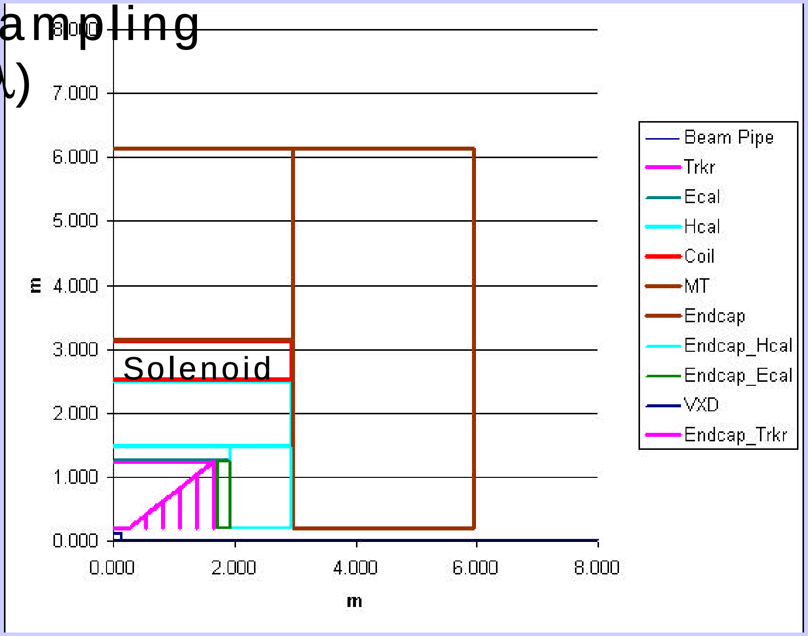
Resource Book L Detector



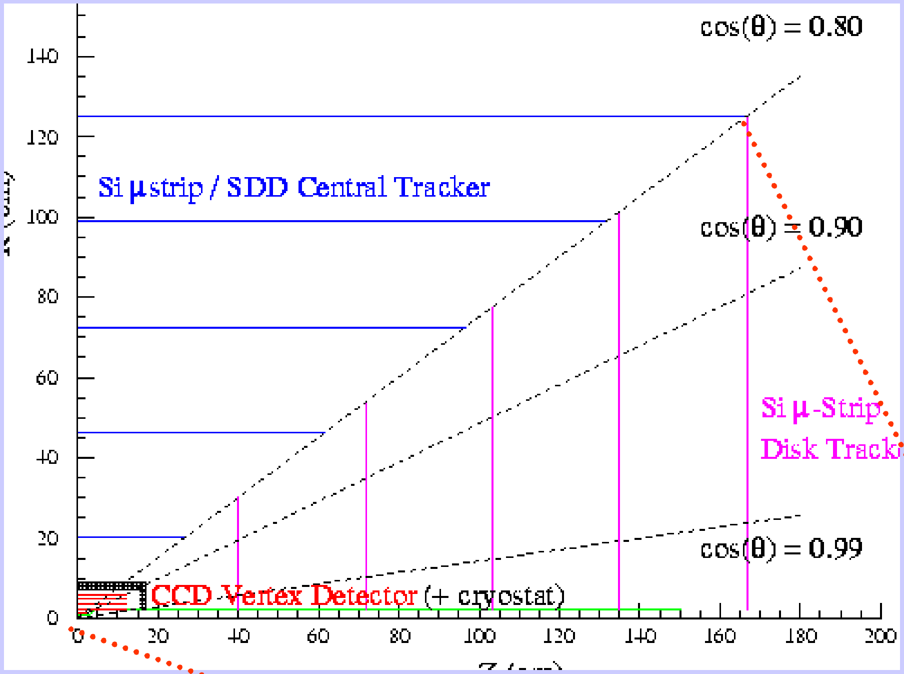


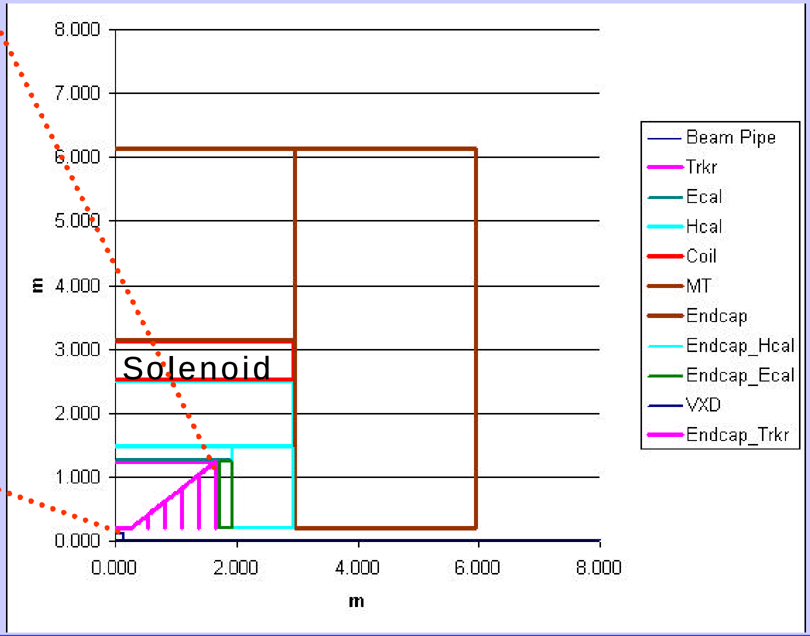
Resource Book SD Detector

5 barrel CCD vertex detector
5 Tesla Solenoid
outside hadron calorimeter
Silicon strips or drift (20 $\rightarrow$ 125 cm) 5 layers
Forward Si discs (5 each)
W/silicon EM calorimeter
0.5 cm pads with 0.7 X_0 sampling
and Cu or Fe Had calorimeter (4 λ)
80 x 80 mrad^2
Muon - 24 5cm iron plates with
gas chambers (RPC?)



Resource Book SD Detector





Resource Book HE Detector Comparison

	L	SD
Solenoid	3 T	5 T
R(solenoid)	4.1 m	2.8 m
BR^2 (tracking)	12 m^2T	8 m^2T
R_M (EM cal)	2.1 cm	1.9 cm
trans.seg / R_M	3.8 0.6 (6th layer Si)	0.26
R_{max}(muons)	645 cm	604 cm

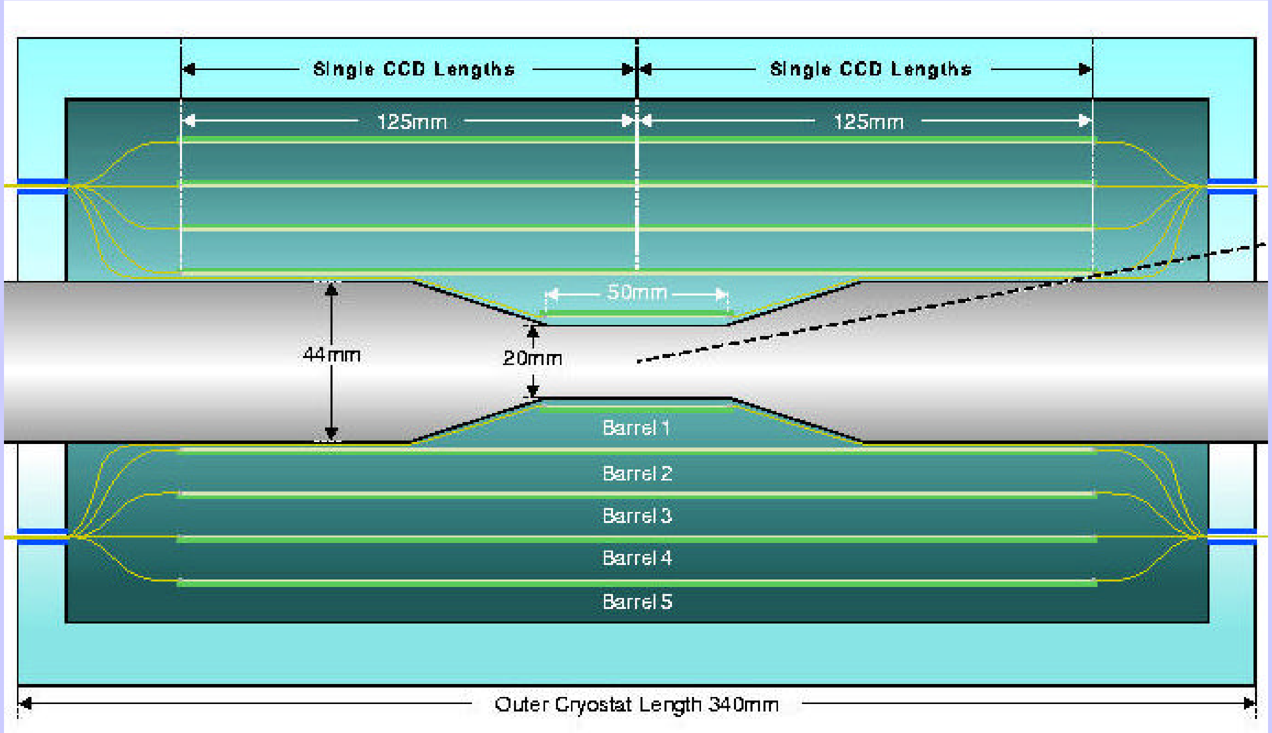
Resource Book P Detector

5 barrel CCD vertex detector
3 Tesla Solenoid
    inside hadron calorimeter
TPC Central Tracking (25 $\rightarrow$ 150 cm)
Pb/scintillator or Liq. Argon EM
  and Hadronic calorimeter
    EM   30 x 30 mrad^2
    Had   80 x 80 mrad^2
Muon - 10 10cm iron plates w/ gas
    chambers (RPC?)

Vertex Detector

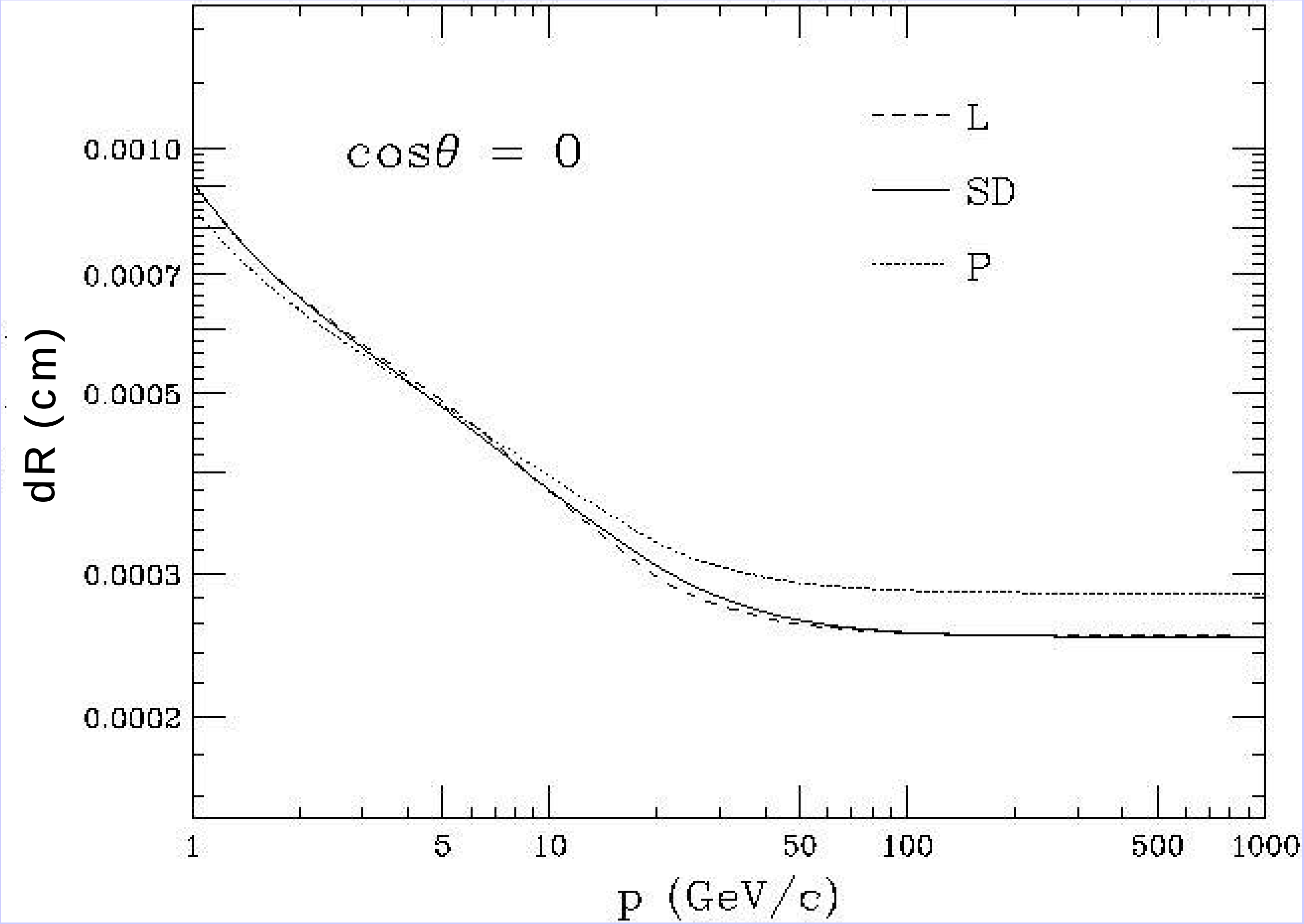
same VXD inside all three detectors (L, SD, and P)
670,000,000 pixels [20x20x20 (μm)^3]
3 μm hit resolution
inner radius = 1.2 cm

5 layer stand-alone tracking



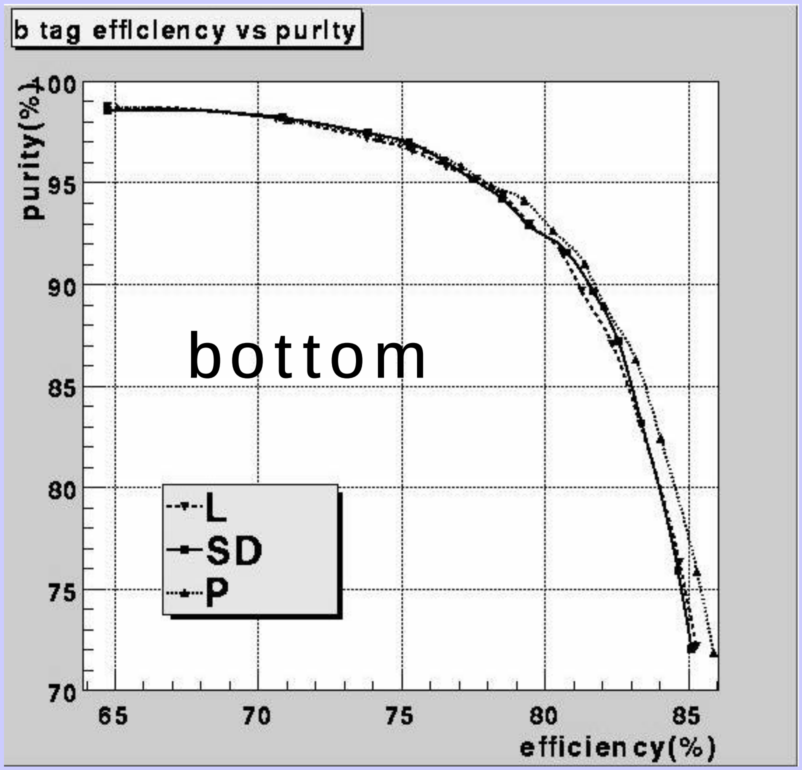
Cos θ
= 0.98

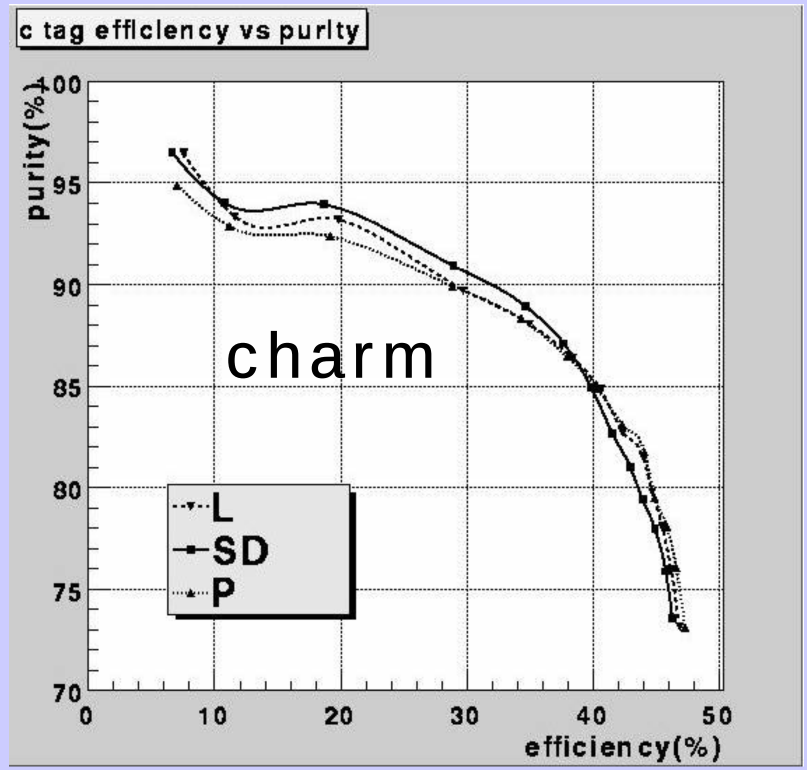
Impact Parameter Resolution



B. Schumm

Flavor Tagging



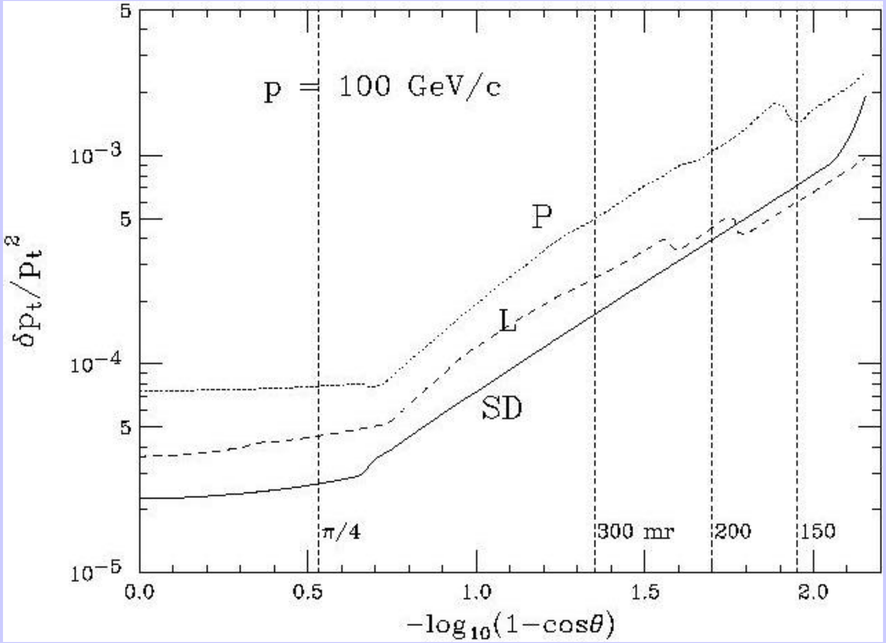


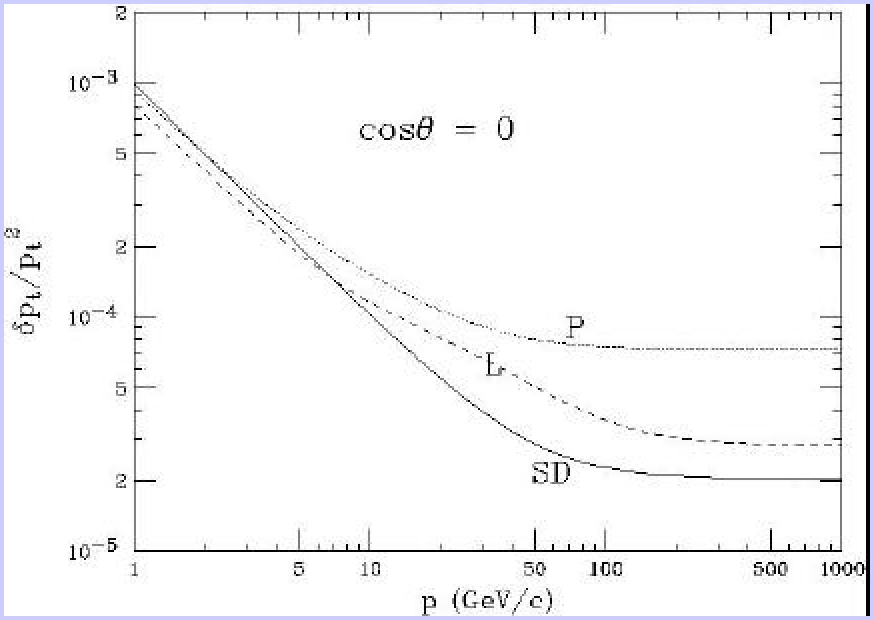
T. Abe

Tracking

	L	SD	P
Inner Radius	50 cm	20 cm	25 cm
Outer Radius	200 cm	125 cm	150 cm
Layers	144	5	122
	TPC	Si drift or μstrips	TPC
Fwd Disks	5	5	5
	double-sided Si	double-sided Si	double-sided Si
B(Tesla)	3	5	3

Tracking Resolution





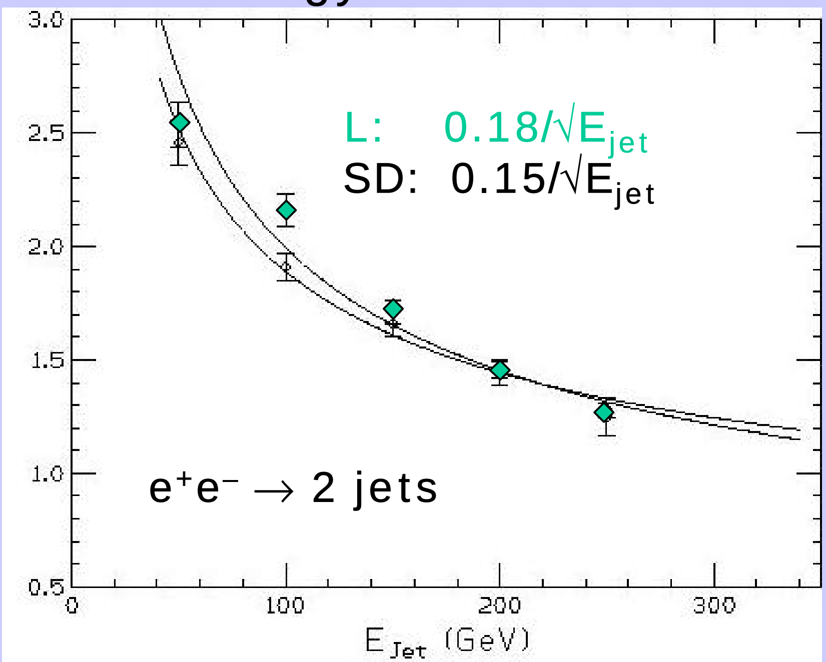
B. Schumm

Calorimeters

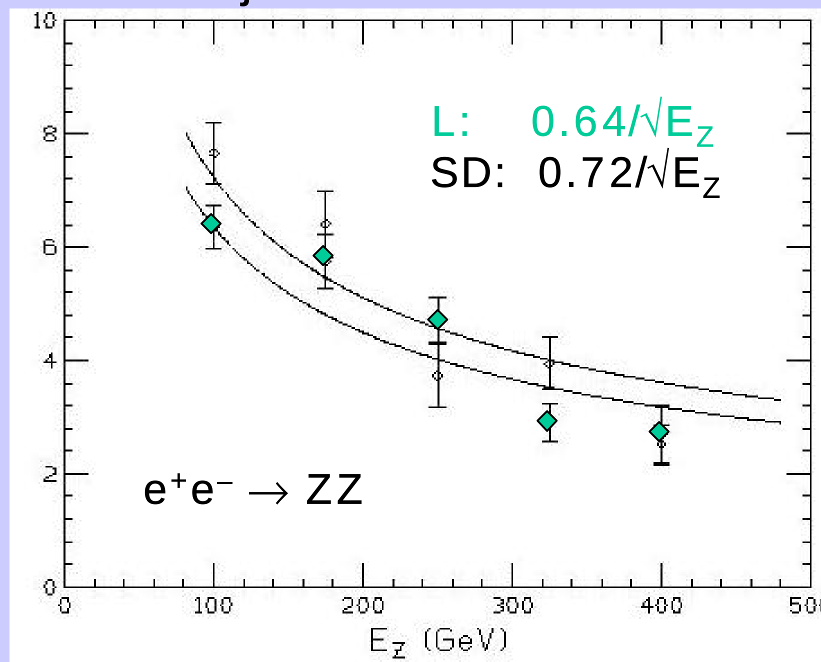
	L	SD	P
EM Tech	Pb/scin (4mm/1mm)x40	W/Si (2.5mm/gap)x40	Pb/scin (4mm/3mm)x32
Had Tech	Pb/scin	Cu or Fe/RPC (or Pb)	Pb/scin
Inner Radius	196 cm	127 cm	150 cm
EM-outer Radius	220 cm	142 cm	185 cm
HAD-outer Radius	365 cm	245 cm	295 cm
Solenoid Coil	outside Had	outside Had	between EM/Had
EM trans. seg.	40 mr	4 mr	30 mr
Had trans. seg.	80 mr	80 mr	80 mr

Calorimeter Resolution

Jet energy resolution



Di-jet mass resolution



These are idealized studies, and resolutions will be worse.

R. Frey

EM resolution:

L: $\sigma_{EM} / E = (17\% / \sqrt{E}) \oplus (\sim 1\%)$

SD: $\sigma_{EM} / E = (18\% / \sqrt{E}) \oplus (\sim 1\%)$

Muon Detection

Model L

24×5 cm Fe plates + RPCs

$\sigma_{r\theta} \approx 1$ cm (x 24) $\sigma_z \approx 1$ cm (x 4)

coverage to ~ 50 mrad

Model SD

24×5 cm Fe plates + RPCs

$\sigma_{r\theta} \approx 1$ cm (x 24) $\sigma_z \approx 1$ cm (x 4)

coverage to ~ 50 mrad

Model P

10×10 cm Fe plates + RPCs

$\sigma_{r\theta} \approx 1$ cm (x 10) $\sigma_z \approx 1$ cm (x 2)

coverage to ~ 50 mrad

NLC Cost Estimates

General considerations:
- Based on past experience
- Contingency = ~ 40%
- Designs constrained

HE IR

L	359.0 M$
SD	326.2 M$

LE IR

P	210.0 M$

NLC Cost Estimates

	L	SD	P
1.1 Vertex	4.0	4.0	4.0
1.2 Tracking	34.6	19.7	23.4
1.3 Calorimeter	48.9	60.2	40.7
1.3.1 EM	(28.9)	(50.9)	(23.8)
1.3.2 Had	(19.6)	(8.9)	(16.5)
1.3.3 Lum	(0.4)	(0.4)	(0.4)
1.4 Muon	16.0	16.0	8.8
1.5 DAQ	27.4	52.2	28.4
1.6 Magnet & supp	110.8	75.6	30.5
1.7 Installation	7.3	7.4	6.8
1.8 Management	7.4	7.7	7.4
SUBTOTAL	256.4	242.8	150.0
1.9 Contingency	102.6	83.4	60.0
Total	359.0	326.2	210.0

Example Issues

1. What are the physics reasons for wanting exceptional jet energy (mass) resolution? How do signal/backgrounds and sensitivities vary as a function of resolution? Is mass discrimination of W and Z in the dijet decay mode feasible, and necessary?

2. How does energy flow calorimetry resolution depend on such variables as Moliere radius, $\Delta\theta/\Delta\varphi$ segmentation, depth segmentation, inner radius, B field, number of radiation lengths in tracker, etc.?

3. What benefits arise from very high precision tracking (e.g. silicon strip tracker); what are the limitations imposed by having relatively few samples, by the associated radiation budget? What minimum radius tracker would be feasible?

4. Evaluate the dependence of physics performance on solenoidal field strength and radius.

The R&D Program

- Many topics require work
- The follow few transparencies list many of the issues
- see also
  - the following talks
  - the report from the International R&D committee

The R&D Program

Calorimetry

energy flow
  need detailed simulation
   followed by prototype beam test demonstration
further develop physics cases for excellent energy flow
    eg. Higgs self-coupling, WW/ZZ at high energy, recon of top and W
      for anomalous couplings?, others (SUSY, BR(H>160))
integrate E-flow with flavor tagging
study readout differences for Tesla/NLC
importance of K0/Lambda in energy flow calorimeter
parametrize E-flow for fast simulation
forward tagger requirements
study effect of muons from collimators/beamline
further development of simulation
    clustering
    tracking in calorimeter
    digital calorimeter
study parameter trade-offs (R seg, layers, coil location, transverse seg.)
  in terms of general performance parameters
  in terms of physics outcome
refine fast-sim parameters from detailed simluation
integrate electronics with silicon detectors in Si/W
reduce silicon detector costs
engineer reduced gaps
mechanical/assembly issues
B = 5 Tesla?
can scintillating tile Ecal compete with Si/W in granularity, etc.?
crystal EM (value/advantages/disadvantages)
barrel/endcap transition (impact and fixes)

The R&D Program

Tracking

refine the understanding of backgrounds
tolerance of trackers to backgrounds
    will large background be a problem for the TPC (field distortions, etc)
    are ionic space charge effects understood?
study pattern recognition for silicon tracker (include vxd)
study alignment and stability of silicon tracker
what momentum resolution is required for physics,
    eg. Higgs recoil, slepton mass endpoint, low and high energy
understand tracker material budget on physics
physics motivation for dE/dx (what is it?)
detailed simulation of track reconstruction, especially for a silicon option,
    complete with backgrounds and realistic inefficiencies
    include CCDs (presumably) in track reconstruction
timing resolution
readout differences between Tesla/NLC time structure
role of intermediate layer
tracking errors in energy flow (study with calorimeter)
forward tracking role with TPC
alignment (esp. with regard to luminosity spectrum measurement)
develop thorough understanding of trade-offs in TPC, silicon options
large volume drift chamber (being developed at KEK)
development of large volume TPC (large European/US collaboration at work)
development of silicon microstrip and silicon drift systems
    (being developed in US & Japan)
study optimal geometry of barrel and forward system
two track resolution requirements (esp. at high energy)
    this impacts calorimetry - how much?
study K0 and Lambda efficiency
    impacts calorimetry?
2D vs. 3D silicon tracker

The R&D Program

Vertx Det

resolve discrepancy in Higgs BR studies
understand degradation of flavor tagging with real physics events
compared to monojets (as seen in past studies)
understand requirements for inner radius, and other parameters
what impact on physics
develop hardened CCDs
develop CCD readout, with increased bandwidth
develop very thin CCD layers (eg. stretched)
segmentation requirements (two track resolution)
500 GeV u,d,s jets
pixel size

Muons

requirements for purity/efficiency vs. momentum on physics channels
understand role in energy flow (work with calorimetry)
detailed simulation
prototype beam tests
mechanical design of muon system
development of detector options, including scintillator and RPCs

The R&D Program

Beamline, etc.

luminosity spectrum measurement
beam energy measurement
polarization measurement
positron polarization
 systematics of the Blondel scheme
veto gamma-gamma very forward system

General

is calibration running at Z^0 peak essential/useful/useless?

Comment

In general it would be good if more work was done exercising the simulation code that has been put together under the leadership of Norman Graf. Much work has been devoted toward developing a detailed full simulation.

North American Leadership

New leadership of Physics and Detectors Working Group
(established by lab directors)

Jim Brau, co-leader
Mark Oreglia, co-leader

<u>Executive Committee</u>
Ed Blucher
Dave Gerdes
Lawrence Gibbons
Dean Karlen
Young-kee Kim
Jeff Richman
Rick van Kooten

North American Leadership

Facilitate the progress of the working groups
in developing the plans for the LC experiments

Issues of focus
- the variables of the LC - how important to physics?
  - time structure
  - energy spectrum
  - energy reach and expansion, luminosity
  - two detectors?
  - Positron polarization
  - Gamma-gamma
  - electron-electron and gamma-electron
- advance the understanding of key detector issues
  - eg. energy flow calorimetry
    - background tolerance
    - vertex detector readout

Coming Meetings

- North American
  - June 27-29, UC-Santa Cruz
- Other regions
  - April 12-15, St. Malo, France (DESY/ECFA)
  - July 10-12, Tokyo, Japan (5th ACFA Workshop)
- International
  - August 26-30, Jeju Is., Korea (LCWS 2002)

Conclusions

The goals for the Linear Collider Detectors will push the state-of-the-art in a number of directions.

eg. finely segmented calorimetry for energy-flow measurement
pixel vertex detectors (approaching a billion pixel system)
integrated readout

Many techniques remain to be understood and developed.

see the following talks

Please get involved in your local effort and connect to the North American effort.

come to Santa Cruz, June 27-29